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# PLANT-DERIVED NATURAL PRODUCTS FROM THE AMERICAN CONTINENT FOR THE CONTROL OF PHYTOPATHOGENIC FUNGI: A REVIEW

**Marco Vinicio Ramirez-Mares[1,*] and Beatriz Hernandez-Carlos[2]**

**[1] Instituto de Recursos, Universidad del Mar, Puerto Ángel, Oaxaca 70902, México;**
**[2]Instituto de Agroindustrias, Universidad Tecnológica de la Mixteca, Huajuapan de León, Oaxaca *69000,* México**
**[*]Corresponding author's e-mail: jvinicio2000@yahoo.com.mx; marcoram@angel.umar.mx**

Various pathogenic microorganisms affect plants. However, most diseases are caused by fungi, which have an enormous reproductive capacity and possess metabolic mechanisms capable to develop resistance to commercial fungicides. Fungi produce mycotoxins on crops and this represents a considerable risk to human and animal health. The most important genera of phytopathogenic fungi of the American continent are: *Aspergillus, Alternaria, Botrytis, Colletotrichum, Fusarium, Phytophthora, Penicillium and Pythium,* among others. Different strategies have been used for phytopatogenic fungi control, mainly by using synthetic fungicides. Currently, a great deal of attention has been paid towards exploitation of higher plant products as an innovative alternative in crops protection. The use of plant derived natural products has many advantages, such as little or no harmful side effects, rare cases of resistance, long-term control and completely or substantially eliminates the use of synthetic fungicides. Several plants belonging to the Anacardiaceae, Asteraceae, Caprifoliaceae, Lamiaceae, Liliaceae, Papilionacea, Poaceae, Verbenaceae, families, have showed fungicide potential. Therefore, this review addresses occurrence of the most important phytopatogenic fungi and the current state of research regarding the potential of vegetable biodiversity in the development of plant derived natural products for the management of these pathogens in the American continent.

**Keywords:** Phytopathogenic fungi, biofungicides, mycotoxins, allelochemicals, crops, integrated pest management

## INTRODUCTION

The total human population is steadily increasing. According to the latest estimates of the Population Reference Bureau (PRB, 2014), the global population reached 7,238 million in 2014 and is projected to increase to 9,683 million in 2050. With approximately 393 thousand births get added each day. The population of Northern America (Canada and United States) will increase from 353 million in 2014 to 444 million in 2050. In contrast, the population in Latin America and the Caribbean will increase from 618 million in 2014 to 773 million in 2050. Such demographic changes would have serious implications for the environment, economy, health and quality of life for the people living in the American Continent. With this population growth, demand will also increase on water, energy, arable land and biological resources to provide adequate food supplies. In 1995 one-third of cropland of the world (1.5 billion hectares) had been abandoned because erosion made it unproductive (Pimentel et al., 1995). Each year about 10 million hectares of fertile cropland are lost due to soil erosion (Pimentel, 2006). In addition, the demand of biofuel will rise from 115 billion L in 2013 to 135 billion L in 2019 (IEA, 2014), that will limit the amount of land available for food production (land-use change), thereby compromising food security, threatening biodiversity or limiting low-income farmers access to land.

In order to provide food for the population which is in permanent augmentation is imperative to increase the production and solve the political and logistical problems of food distribution (Zhang, 2009). This is the current challenge for agriculture. More recent the Food and Agricultural Organization (FAO) estimates, indicate that 47 million people living in Latin America and the Caribbean were unable to meet their dietary energy requirements in 2011-2013 (FAO, 2013). The decrease losses of food during pre-harvest and post-harvest, can provide an effective way to increase food availability and reduce the land need for its production (Kader, 2005). Food are very prone to microbial spoilage, infection by microorganisms (bacteria, viruses, fungi, nematodes, phytoplasmas and viroids) that cause postharvest decay can occur before the harvest and can remain latent until storage, when environmental condition favor their development. Most diseases and crop production losses are caused by phytopathogenic fungi which are able to infect any tissue at any stage of plant growth (Agrios, 2005). Plant pathogenic fungi are characterized by high complexity and diversity, these biological variability allow them to growth in very climatologically different environments, since dry zones until wet hot regions (Agrios, 2005). Moreover, fungal spores are more durable and long-lived than other microorganisms, can easily hitch rides on humans and as humans move around the world, fungi of all kinds are landing in new habitats. Recently, Dean et al., (2012) published the Top 10 fungal plant pathogen list, based on scientific/economic importance. The Top 10 list includes, in rank order, (1) *Magnaporthe oryzae*; (2) *Botrytis cinerea*; (3) *Puccinia* spp.; (4) *Fusarium graminearum*; (5)

*Fusarium oxysporum*; (6) *Blumeria graminis*; (7) *Mycosphaerella graminicola*; (8) *Colletotrichum* spp.; (9) *Ustilago maydis* and (10) *Melampsora lini*.

In fruits, vegetables and cereals, there is a wide variety of fungal genera causing quality problems related to organoleptic characteristics, appearance, nutritional value and limited shelf life (Yanes et al., 2012; Dean et al., 2012). In addition, the production of mycotoxins by several fungi is responsible for allergic or toxic disorders among humans and livestock (Díaz-Dellavalle et al., 2011). More than 300 fungal metabolites are reported to be toxic to animals and man (Galvano et al., 2001). Fungal proliferation and mycotoxins occur more frequently in regions with high temperatures, high moisture, flash floods and unseasonal rains during harvest. Beyond good horticultural and agronomic practices, growers often rely on pesticides and fertilizers. The use of pesticides is essential in agriculture production, the loss of cereals, vegetables and fruits from pest injury would reach 32%, 54% and 78% respectively, without pesticides application (Cai, 2008). Synthetic fungicides are still the most important components in the management of fungal plant diseases (Croplife, 2012). Even though the use of synthetic fungicides controls the seed borne fungi seeds in an effective and efficient way, enabling the plants to grow to their maximum genetic potential, they cannot applied to grains due to pesticide toxicity (Harris et al., 2001). The usefulness of synthetic fungicides are increasingly limited owing to toxicity to non-target organisms, development of resistance by pathogens, residual toxicity problems, pathogen resurgence, environmental pollution and public concerns about the harmful effects on human health (Sharma and Meshram, 2006; Wu et al., 2010). Over the past few years there has been an increasing political pressure to remove the most hazardous fungicides from the market and to develop formulation with less negative impacts. Thus, it is believed (Gullino et al., 2000) that fungicides should be optimized under integrated pest management (IPM) and the best option is to use eco-friendly approaches.

Plant derived fungicides used as extracts, essential oils or pure allelochemicals have enormous potential against plant pathogenic fungi, because the secondary metabolism of plants has evolved to protect them against microbial pathogens (Benner et al., 1993; Mabrouk, 2012; Elamathi et al., 2012). Higher plants contain a wide spectrum of secondary metabolites such as tannins, coumarins, alkaloids, phenolic compounds, quinones and phytoalexins, which have antifungal activity (Kagale et al., 2004). Biofungicides possess the following advantages; strong specificity, degrade to nontoxic products within a few days (eco-friendly), they are not phytotoxic, can be modified to improve performance and enhance quality and rare cases of resistance (Siddiqui and Gulzar, 2003; Gupta and Dikshit, 2010). The source plants for the biofungicides are endemic of the developing countries in America (most of the Latin America and the Caribbean countries); in these countries the benefit will be great if the eco-friendly biofungicides are part of an IPM strategy.

***Phytopathogenic Fungi Identified In The American Continent :*** Fungi is an extensive group of eukaryotic microorganisms (Garrido et al., 2012), it is considered that ninety percent of plant pathogens are fungi (Buckley, 2008). Most of the plants can be attacked by some kind of fungus (or more) and is also known that the same phytopathogenic fungus can infect one or more types of plants, even of different families (O'Donnell et al., 2000; Agrios, 2005). Plant pathogenic fungi show a complex life cycles, the reproduction is primarily via spores (one or a few cells), that could be produced by sexual and asexual reproduction stages (Pérez-Martin and de Sena-Tomas, 2011; Garrido et al., 2012; Phillipson, 2012). The phytopathogenic fungi spend most of their life cycle in the plant, which serves as host, and other part of their cycle in the soil, on plant debris found there (as saprophytes), although some only develop as parasites (Crous et al., 2009). Generally, fungal reproductive bodies are formed on the surface of tissues of the host plant (or very close), which causes that the spores are able to disperse quickly and easily (O'Donnell et al., 2000; Garrido et al., 2012). Diseased plants differ morphologically and physiologically from healthy individuals (Rostás et al., 2003). The effects produced by fungi on plants may be of local type; when they affect a small tissue, or general damage, which depends of the type of fungus and plant infected (Garrido et al., 2011; Phillipson, 2012). The damage caused by the fungus is primarily a death of infected tissue (Rostás et al., 2003); showed as 'green islands', which are spots of photosynthetically active tissue surrounded by chlorotic areas, as well as wilted leaves, give plants with an altered appearance (Hatcher et al., 1994; Phillipson, 2012). The pathogen can also cause atrophy of the complete plant or small part, and in other cases they may cause excessive growth or hypertrophy, such as; galls, warts or tumors on the roots (Hardham, 2001; Phillipson, 2012). For fungi that affect the root, or the vascular system of the plant, the production of a yellow color in the plant blight is backed. The above effects can cause atrophy of the plant, which eventually lead to the death of the host (D'Mello and Macdonald, 2003). A comprehensive knowledge on the nature of plant hosts and the manner in which the healthy plants get infected is essential, in order to check the infiltration of host plant environment by different fungal pathogens. The following properties appear to be hallmarks of phytopathogen fungi: 1) highly developed infection structures; 2) limited secretory activity, especially of lytic enzymes; 3) carbohydrate-rich and protein-containing interfacial layers that separate fungal and plant plasma membranes; 4) long-term suppression of host defense; and 5) haustoria, which are specialized hyphae for nutrient absorption and metabolism (Mendgen and Hahn, 2002).

These pathogens also could cause disease (e.g., infections, allergies) in man, and produce toxins that affect plants, animals and humans (De Lucca, 2007). Mycotoxins are toxic substances produced mostly as secondary metabolites by filamentous fungi that grow on seeds, grains, and feed in the field, or in storage, five fungal genera produce these metabolites (*Penicillium, Aspergillus, Fusarium, Claviceps*

**Table 1. Major mycotoxins prevalent in the American continent**

| Fungal species | Mycotoxin | Human health problem | References |
|---|---|---|---|
| *Alternaria alternata, A. arborescens, A. tenuissima, A. solani, Alternaria sp., Alternaria spp., A. tagetica* and *A. zinniae* | Belong to three structural classes: the tetramic acid derivative, tenuazonic acid (TA); the dibenzopyrone derivatives, alternariol (AOH), alternariol methylether (AME) and altenuene; and the perylene derivatives, the altertoxins. Solanapyrones and zinnolide. Zinniol derivatives. | AOH and AME are mutagenic and cytotoxic to mammalian cells, and are suspected to be carcinogenic. They are one of the most common airborne allergens, as well as being one causative agent of phaeohyphomycosis in immunocompromised patients. Possible toxic and foetotoxic effect. Genotoxic, mutagenic, carcinogenic and cytotoxic effects. Mutagenic and clastogenic in various in vitro systems. Might be responsible for esophageal cancer. | Greco et al., 2012; Gambale et al., 1976; Pollock et al., 1982; Biggs et al., 1993; Biggs, 1995; Gamboa-Angulo et al., 2000; Gamboa-Angulo et al., 2002; Andersen et al., 2008; Andrew et al., 2009; Lourenco et al., 2009; Alexander et al., 2011; Díaz Dellavalle et al., 2011; Somma et al., 2011; Edin, 2012; Pavón-Moreno et al., 2012; Benavidez Rozo et al., 2013 |
| *Aspergillus brasiliensis, A. costaricaensis, A. flavus, A. lacticoffeatus, A. nidulans* and *A. niger.* | Chaetocin, penitrem A, and xanthocillin , tenuazonic acid, aflatoxin G2, aflatoxin B1 and B2, chaetoglobosin C, ochratoxin A and spinulosin. | Potential liver carcinogens in humans. Also, increases risk of hepatocellular carcinoma in patients with chronic hepatitis B virus. Induce allergic disorders, such as; allergic asthma, allergic rhinitis, allergic sinusitis, allergic bronchopulmonary aspergillosis (ABPA), and hypersensitivity pneumonitis. Patients with cystic fibrosis are often reported to have complication of ABPA. | Banerjee and Kurup, 1998; Wogan, 1999; Freire et al., 2000 |
| *Bipolaris oryzae* and *B. sorokiniana* | Cochlioquinones and ophiobolins. | Cochlioquinones are antagonists of the Human Chemokine Receptor CCR5. | Manandhar et al., 1998; Yoganathan et al., 2004; Consolo et al., 2012 |
| *Botryodiplodia theobromae* | Botryodiplodin, (+)-7-iso-jasmonic acid and several minor jasmonates. | Botryodiplodin induces DNA-protein cross-links in mammalian cells. | San Gupta et al., 1966; Moulé et al., 1982; Hertel et al., 1997; Ramezani et al., 2007 |
| *Botrytis cinerea* | Botrydial. | No reported to date. | Latorre et al., 2002; Muñoz et al., 2002; Daoubi et al., 2006; Asadollahi et al., 2013 |
| *Claviceps spp.* | Toxic alkaloids. | Toxic amounts of alkaloids leading to the disease known as ergotism in humans and other animals consuming them. The Holy Fire or St. Anthony's Fire is the primary vascular manifestation, causing burning pain and gangrene in the feet and hands. | Richard et al., 2003; Alm and Elvevag, 2013; Ayarragaray, 2014 |
| *Fusarium avenaceum, F. culmorum, F. graminearum, F. decemcellulare, F. moniliforme, F. oxysporum, F. sambucinum, F. sporotrichum, F. spp., F. solani* and *F. verticillioides* | Fumonisins and Zearalenone. | These toxins have been shown to be carcinogenic in rats and mice. Seem to be the most likely cause of human esophageal cancer. They are considered to be potential causes of immunosuppression in humans leading to secondary disease. | Richard et al., 2003; Prandini et al., 2009; Tittlemier et al., 2013b |
| *Penicillium expansum* and *P. herquei.* | Ochratoxin. | It is a genotoxic carcinogen by induction of oxidative DNA lesions coupled with direct DNA adducts via quinone formation. | Richard et al., 2003; Pfohl-Leszkowicz and Manderville, 2007; Hope and Hope, 2012 |

**Table 2. Important fungal phytopathogens in the American continent**

| Fungal species | Plant Disease | Country | References |
|---|---|---|---|
| *Alternaria alternata, A. arborescens, A. tenuissima, A. solani, Alternaria sp., Alternaria spp., A. tagetica* and *A. zinniae* | Fruit rot of blueberry is the most common and severe postharvest problem. Spoiled tomatoes. Early blight on potato. Fruit rot of apple, pear, melon, apricot, grapes, raisins, strawberry, olive, citrus fruits and dried figs. Citrus fruits, olives and several other fruits and vegetables. | Argentina, USA, Canada, Mexico and Brazil. | Greco et al., 2012; Gambale et al., 1976; Biggs et al., 1993; Biggs, 1995; Gamboa-Angulo et al., 2000; Gamboa-Angulo et al., 2002; Andrew et al., 2009; Alexander et al., 2011; Díaz Dellavalle et al., 2011; Somma et al., 2011; Pavón-Moreno et al., 2012; Benavidez Rozo et al., 2013 |
| *Aspergillus brasiliensis, A. costaricaensis, A. flavus, A. lacticoffeatus, A. nidulans* and *A. niger.* | Black and White pepper. Nut kernels. Black rot of grapes, which subsequently may result in ochratoxin A contamination of grapes, grapes by-products, dried vine fruits, coffee, and cocoa | Brazil, Costa Rica and Venezuela. | Freire et al., 2000; Perrone et al., 2011; Adjovi et al., 2014 |
| *Bipolaris oryzae* and *B. sorokiniana* | They cause major foliar disease and grain discoloration on cereals, such as; rice, maize and sorghum, to cause a brown leaf spot disease | Argentina. | Manandhar et al., 1998; Consolo et al., 2012 |
| *Blumeria graminis* | Also is called the grass powdery mildew fungus and causes serious damage to a variety of cereal crops. | USA, Canada and Mexico. | Wyand and Brown, 2003; Inuma et al., 2007; Sánchez-Martín et al., 2011 |
| *Botryodiplodia theobromae* | Infection of cocoa beans. | USA. | San Gupta et al., 1966; Fessehatzion and Olutiola, 1987; Ramezani et al., 2007 |
| *Botrytis cinerea* | Spoiled tomatoes. Also, is the most important disease of table grapes (Vitis vinifera L.) | Chile and Argentina. | Latorre et al., 2002; Muñoz et al., 2002; Asadollahi et al., 2013 |
| *Cladosporium herbarum C. sp.* | Causes a Leaf Spot on Marshmarigold (*Caltha* spp.) are members of the buttercup family (Ranunculaceae) and inhabit stream banks and wet meadows in subalpine habitats of the Rocky and Cascade Mountains. | USA. | Lago et al., 2004; Rodríguez-Rajo et al., 2005; Johnson et al., 2008 |
| *Claviceps* spp. | This organism is known as a replacement parasite in that it replaces plant structures with fungal tissue called ergots or sclerotia. | Argentina and USA. | Richard et al., 2003; Fisher et al., 2005 |
| *Colletotrichum acutatum, C. coccodes, C. fragariae, C. graminicola, C. gloeosporioides, C. lindemuthianum, C. spp.* and *C.truncatun.* | Citrus postbloom fruit drop epidemics and legume species. Is the cause of anthracnose with black sunken lesion. Affect tomato, onions and dry bean cultures. | Brazil, Canada and USA. | Buchwaldt et al., 2004; Rodríguez-Rajo et al., 2005; Hernández-Silva et al., 2007; Ciampi-Guillardi et al., 2014; Yang et al., 2014 |
| *Macrophomina phaseolina.* | Affects: Tallgrass prairie, maize, soybean and sorghum. | Brazil and USA. | Baird et al., 2010; Saleh et al., 2010; Schinke and Germani, 2012; Iqbal and Mukhtar, 2014 |
| *Phytophthora infestans, P. plurivora* and *P. ramorum.* | The causal agent of the late blight of solanaceous plant species, which can devastate potato and tomato crops. | Mexico and USA. | Del Castillo-Munera et al., 2013; Eyre et al., 2013; Martín et al., 2014; Schoebel et al., 2014 |
| *Phymatotrichum omnivorum.* | Phymatotrichum (cotton or Texas) root rot is caused by the soil-borne fungus. | USA. | Gunasekaran and Ahuja, 1975; Uppalapati et al., 2010 |
| *Pythium sp and P. ultimum.* | Causes a variety of diseases including seed rots and damping-off, root, stem and fruit rots, foliar blights and postharvest decay. | Canada and USA. | Vaartaja, 1974; Pane et al., 2011; Taylor et al., 2002 |
| *Rhizoctonia solani.* | Causes black scurf on potato tubers, stolon and root pruning, and stem canker on above ground plant parts. Black scurf is characterised by the presence of black sclerotia on the tuber surface which result in a significant tuber blemish. | Colombia. | Gonzalez-Vera et al., 2010; Ferrucho et al., 2013; Thangavel et al., 2014 |
| *Fusarium avenaceum, F. culmorum, F. graminearum, F. decemcellulare, F. moniliforme, F. oxysporum, F. sambucinum, F. sporotrichum, F. spp., F. solani* and *F. verticillioides* | They are causes of wilts and scab or blight diseases of small grains and ear rot. Affect grains such as wheat, barley, oats, and corn. | Argentina, Canada, Uruguay and USA. | Richard et al., 2003; Sampietro et al., 2011; Poole et al., 2013; Tittlemier et al., 2013a; Umpierrez-Failache et al., 2013; Malbrán et al., 2014 |
| *Penicillium expansum* and *P. herquei.* | Is the primary cause of blue mold, a common postharvest fruit rot disease of apple. | Argentina and USA. | Li and Xiao, 2008; Finn et al., 2013; Rouissi et al., 2013 |

and *Alternaria*) (Anjorin et al., 2013). The most prevalent classes of mycotoxins are; aflatoxins, trichothecenes (e.g., deoxynivalenol, T-2 toxin), zearalenone, ochratoxins, and fumonisins (Table 1). When ingested, inhaled, or absorbed through skin, mycotoxins may reduce appetite and general performance, and cause sickness or death in humans (Tanaka et al., 2007; Kumar et al., 2008) The global occurrence of mycotoxins is considered to be a major risk factor, according to FAO (2012), 25% of the world's commodities are annually affected by known mycotoxins. Mycotoxins are formed in the field during the growing season; however, they also are formed or increased during harvest, drying, and storage (Richard et al., 2003). In the United States only, the mean economic annual costs of crop losses caused by mycotoxins are estimated to be 932 million USD (Richard et al., 2003). During the last decade, the problem of these pathogenic fungal infections in American Continent, has reached epidemic proportions (O'Donnell et al., 2000; Bruin and Sabelis, 2010; Barres et al., 2012). The classification of plant pathogenic fungi considers the host range and disease symptoms produced, but a problem arises when morphologically similar fungi produce similar disease symptoms, but have no clearly defined host range (Taylor and Pedras, 1995). In this review, we present a compilation of the most important phytopathogenic fungi in our continent (Table 2).

***Vegetable Extracts With Antifungal Activity :*** A total of 143 plants from America, belonging to 43 botanical families (109 genera) possess toxic activity against phytopathogenic fungi species of 28 genera (Table 3). These pathogens attack crops, stored grains, seeds and food products, and include species of *Alternaria, Aspergillus, Bipolaris, Botryodiploida, Botrytis, Cladosporium, Colletotrichum, Corynespora, Curvularia, Drechslera, Epicoccum, Exserobilum, Fusarium, Gaeumannomyces, Geotrichum, Gerlachia, Leptosphaeria, Macrophomina, Monilia, Moniliophthora, Mycosphaerella, Neurospora, Penicillium, Pestalotia, Phaeoisariopsis, Phomopsis, Pyricularia, Pythium, Rhizopus, Sarocladium, Sclerotinia, Sclerotium, Sitophilus, Sporothrix, Trichoderma* and *Trichophyton* genera. The botanical families with the highest number of species with antifungal activity are Asteraceae (22), Fabaceae (18), Lamiaceae (13), Rutaceae (9), Verbenaceae (8), Euphorbiaceae (8) and Poaceae (7). There are 61 plants fungicides against *Colletotrichum* genera, followed by 42 plants with toxic activity against *Fusarium* and *Alternaria* species, while only one toxic vegetal specie for the following genera is described; *Drechslera, Epicoccum, Gaeumannomyces, Leptosphaeria, Monilia, Mycosphaerella, Neurospora, Pestalotia, Sitophilus, Trichoderma,* and *Trichophyton*. Plant treatments for fungicide tests were mixtures of essential oils (Jaramillo et al., 2012; Landero-Valenzuela et al., 2013), or methanol, ethanol, dichloromethane, chloroform, and aqueous extracts. Some authors considered alternatives to the practical application of treatments, using non-common solvent extracts as cocoa butter and lanolin (Castillo et al., 2010) or added to chitosan edible films (Avila-Sosa et al., 2012). In addition, treatment of plant or extracts to improve the antifungal activity was used, such as the fermentation of aqueous extracts of *Flourensia cernua* (De León et al., 2013), which were most effective against *F. oxysporum* than those prepared in ethanol (Jasso de Rodríguez et al., 2007). In addition, the abiotic elicitation (UV light) of *Brassica oleracea* was used to produce the toxic caulilexins A-C to *Leptosphaeria maculans, Rhizoctonia solani, and Sclerotinia sclerotiorum* (Pedras et al., 2006).

***Compounds With Fungicide Activity*** **Essential oils:** Gas chromatography-mass spectrometry analysis of mixtures of essential oils with fungicide activity show as main compounds: 1,8-cineole, 4-carene, 5-methylfurfural, benzene acetaldehyde, borneol, isocaryophyllene, carvacrol, caryophyllene, citral, elemol, germacrane D, germacrene, hexadecanoic acid, limonene, *m*-cymene, methylcinnamate, methyl-eugenol, *n*-nonanal, *p*-cymene, sabinene, safrole, spathulenol, thymol, *trans*-cinnamaldehyde, α-bisabolol, α-cadinol, α-terpinene, α-terpinyl acetate, β-myrcene, β-phellandrene, 5-phenyl-1,3-pentadiene, capillarin, and β-pinene (Table 3). However, some authors showed the fungicide activity of isolated compounds, such as 5-methylfurfural, benzene acetaldehyde, *n*-nonanal, and carvacrol, all actives against *Colletotrichum* species (Kobaisy et al., 2001; Demirci et al., 2006). Also, it was described the synergistic fungicidal activity of compounds present in the essential oil mixture from *Chrysothamnus nauseosus* against *Botrytis cinerea*, with more than 50 identified compounds, where non-major component showed this toxic activity (Tabanca et al., 2007).

***Other Compounds with Fungicide Activity*****:** Although Asteraceae is the family most studied, from Fabaceae species have been isolated more fungicides compounds, different to that found in essential oils (Figure 1). Diterpenoid 1 (Cotoras et al., 2004) and bicyclic sesquiterpenic alcohol (2) are toxic to *Botrytis* (Ortíz-Nuñez et al., 2007). Other terpenes are 15,16-dihydroxypimar-8(14)-en-3-one (3), fungicide against *Colletotrichum gloeosporioides* (Peraza-Sánchez et al., 2005) and the sesquiterpenes polygodial (4), drimenol, drimenin, and isodrimenol that inhibited the growth of *Gaeumannomyces graminis (*Monsálvez et al., 2010). Compound 1 produces permeabilization of the cell membrane of *B. cinerea* through the induction of *p*-nitrophenyl butyrate esterase and laccase production (Cotoras et al., 2004). Twelve bioactive alkaloids (Figure 1) were described; among various structures, the amide type 6 and 12, resulted toxic to *Sclerotium* and *Botrytis* species respectively (Meepagala et al., 2010; Ramírez-Chávez et al., 2000). Quinoline alkaloids as 7, 11, 2-*n*-nonyl-4-quinolone, and 13 were active against *Alternaria, Epicoccum, Pestalotia, Drechslera, Fusarium, Colletotrichum* and *Botrytis* species (Oliva et al., 2003; Li et al., 2005). While those of the pyrrol type as caulexin A (5), B and C were toxic to *Leptosphaeria, Rhizoctonia, Sclerotinia* (Pedras et al., 2006); and quinolizidine alkaloids

**Table 3. Vegetable species from America with antifungal activity**

| Family | Specie | Patogen | Observations | References | Country |
|---|---|---|---|---|---|
| Amaranthaceae | *Chenopodium ambrosiodes* | *Fusarium oxysporum* | Growth inhibition by essential oils (α-terpinene, *p*-cymene, 4-carene) | Jaramillo et al., 2012 | Colombia |
| | *Teloxys ambrosoides (Chenopodium ambrosioides)* | *Fusarium sp.* | Growth inhibition by essential oils | Barrera-Necha and García-Barrera, 2008 | Mexico |
| Amaryllidaceae | *Allium sativum* | *Drechslera tritici-repentis, Bipolaris sorokiniana* | Garlic extract and allicin protect wheat seed infected | Perelló et al., 2013 | Argentina |
| | | *Colletotrichum gloeosporioides* | Growth, germination and sporulation inhibition of essential oils *in vitro* and *in vivo* assays | Landero-Valenzuela et al., 2013_ | Mexico |
| Anacardiaceae | *Myracrodruon urundeuva* | *Fusarium decemcellulare, F. monoliforme, F. oxysporum, F. solani* | Growth inhibition by extracts (gallic acid, flavonoids, luteolin, cinnamic derivatives, proanthocyanidins, hydrolysable tannins, and leucoanthocyanidins) | Sá et al., 2009 | Brazil |
| Asparagaceae | *Agave lechuguilla* | *Colletotrichum gloeosporioides, Penicillium digitatum* | 500-5000 µL/L produces 90% sporulation inhibition 500-3000 µL/L >55% growth inhibition | Jasso de Rodríguez et al., 2011 | Mexico |
| | | *Rhizoctonia solani* | Extracts with polyphenols showed growth inhibition ($CI_{50}$ 32.5 ppm) | Castillo-Reyes et al., 2015 | Mexico |
| | *Yucca carnerosan* | *Rhizopus stolonifer, Colletotrichum gloeosporioides, Penicillium digitatum* | Growth inhibition 3000-5000 µl/L 80% 3000 µl/L sporulation inhibition | Jasso de Rodríguez et al., 2011 | Mexico |
| | *Yucca filifera* | *Rhizopus stolonifer, Colletotrichum gloeosporioides, Penicillium digitatum* | Growth inhibition 2000 µl/L Sporulation inhibition 1000 µl/L | Jasso de Rodríguez et al., 2011 | Mexico |
| Apocynaceae | *Allamanda blanchetti* | *Fusarium sp., Cladosporium sp., Curvularia sp., Alternaria sp.* | Ethanol extracts protects *Pterogyne nitens* seeds at 100 and 500 ppm | Ferreira-Medeiros, et al., 2013 | Brazil |
| | *Calotropis procera* | *Fusarium solani Colletotrichum gloeosporioides, Neurospora sp.* | Growth inhibition 20,100 Da-Protein $IC_{50}$ 32.1-67 µg/mL | Teixeira de Freitas et al., 2011 | Brazil |
| Asparagaceae | *Furcraea cahum* | *Alternaria tagetica, Colletotrichum gloeosporoides* | Growth inhibition by ethanol extract | Gamboa-Angulo et al., 2008 | Mexico |
| | *Bonellia flammea* | *Curvularia verruculosa, C. lunata, Exserobilum rostratum, Corynespora cassiicola,* | Aqueous extracts showed growth mycelial growth >50%, sporulation inhibition >58% (*C. verruculosa, E. rostratum, C. lunat*a) and germination inhibition >73% (*C. verruculosa, E. rostratum, C. lunat*a, *C. cassiicola*) | Moo-Koh et al., 2014 | Mexico |
| Asteraceae | *Adenophyllum aurantium* | *Fusarium solani, Alternaria alternata* | Sporulation and mycelial growth inhibition (MIC 7.78-27 mg/mL) by methanol and ethyl acetate extracts from roots and aerial parts. | Lira de León et al., 2014 | Mexico |
| | *Ageratum conyzoides* | *Aspergillus flavus* | Essential oils at > 0.1µg/mL inhibited mycelial growth and aflatoxins production | Nogueira et al., 2010 | Brazil |
| | *Ambrosia hispida* | *Alternaria tagetica, Colletotrichum gloeosporioides* | Growth inhibition by ethanol extract | Gamboa-Angulo et al., 2008 | Mexico |
| | *Alloispermum integrifolium* | *Fusarium solani, Alternaria alternata* | Sporulation inhibition (MIC 16.88-33.76 mg/mL) by methanol extracts from aerial parts | Lira de León et al., 2014 | Mexico |
| | *Arnica longifolia* | *Colletotrichum acutatum, C. fragarie, C.* | Growth inhibiton by essential oils (carvacrol and α-bisabolol) | Tabanca et al., 2007 | USA |

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| | | *gloeosporioides,* | | | |
| | *Artemisia annua* | *Alternaria alternata* | Growth inhibition *in vitro* but not *in vivo* by methanol extract | Carvalho et al., 2011 | Brazil |
| | *Artemisia dracunculus* | *Colletotrichum fragariae, C. gloeosporioides, C. accutatum* | Growth inhibition by essential oils (Methyl-eugenol) | Meepagala et al., 2002 | USA |
| | *Artemisia ludoviciana* | *Colletotrichum lindemuthianum* | Growth and spore germination inhibition (borneol, spathulenol, derivatives of caryophyllene and spathulenol) | Damián-Badillo et al., 2008 | Mexico |
| | *Aster hesperius* | *Colletotrichum accutatum, C. fragariae, C. gloeosporioides,* | Growth inhibition by essential oils (hexadecanoic acid, carvacrol) | Tabanca et al., 2007 | USA |
| | *Calea urticifolia* | *Alternaria tagetica* | Growth inhibition by ethanol extract | Gamboa-Angulo et al., 2008 | Mexico |
| | *Conyza canadensis* | *Colletotrichum acutatum, C. fragariae, C. gloeosporioides* | Growth inhibition by (4Z,8Z)-matricaria lactone (**43**) | Queiroz et al., 2012 | USA |
| | *Chrysactinia mexicana* | *Aspergillus flavus* | Growth inhibition by essential oils | Cárdenas-Ortega et al., 2005 | Mexico |
| | *Chrysothamnus nauseosus* | *Colletotrichum acutatum, C. fragarie, C. gloeosporioides* | Growth inhibition by essential oils (β-phellandrene and β-pinene) | Tabanca et al., 2007 | USA |
| | *Cynara scolymus* | *Alternaria spp* | Growth inhibition by aqueous extract at MIC 5µg/mL and saline buffer and acid extracts at MIC 10µg/mL | Díaz-Dellavalle et al., 2011 | Uruguay |
| | *Fluorensia cernua* | *Fusarium oxysporum, Penicillium expansum* | Fermented extract produces growth inhibition at 500 ppm | De León et al., 2013 | Mexico |
| | | *Rhizoctonia solani* | Cocoa butter extract produces growth inhibition $CI_{50}$ 420 ppm | Castillo et al., 2010 | Mexico |
| | | | Extracts with polyphenols showed growth inhibition ($CI_{50}$ 16.3 ppm) | Castillo-Reyes et al., 2015 | Mexico |
| | | *Fusarium oxysporum, Alternaria sp., Rhizoctonia solani* | Total growth inhibition at ≤1500µl/l by ethanol extract | Jasso de Rodríguez et al., 2007 | Mexico |
| | *F. retinophylla* | *Fusarium oxysporum, Alternaria sp., Rhizoctonia solani* | Total growth inhibition at ≤1500µl/l by ethanol extract | Jasso de Rodríguez et al., 2007 | Mexico |
| | *Haplopappus greenei* | *Colletotrichum acutatum, C. fragariea, C. gloeosporioides* | Growth inhibition by essential oils (carvacrol) | Demirci et al., 2006 | USA |
| | *Heliopsis longipes* | *Sclerotium cepivorum, S. rolfsii* | Growth inhibition by alkamide affinin (**17**) | Ramírez-Chávez et al., 2000 | Mexico |
| | | *Colletotrichum lindemuthianum, Sporothrix schenckii* | Growth and germination inhibition by chloroform and methanol extracts | Damián-Badillo et al., 2008 | Mexico |
| | *Mutisia friesiana* | *Cladosporium cucumerinum* | Moderate growth inhibition by 5-methylcoumaranones (**30**-**33**) | Viturro et al., 2004 | Argentina |
| | *Pseudognaphalium vira vira* | *Botrytis cinerea* | Growth inhibition by 3β-hydroxy-kaurenoic acid (**3**) | Cotoras et al., 2004 | Chile |
| | *Tagetes erecta* | *Rhizoctonia solani Kühn* | Growth inhibition by aqueous extract at 0.5 g/mL | Espejo-Quispe et al., 2010 | Cuba |
| | *T. lucida* | *Colletotrichum lindemuthianum, Sporothrix schenckii* | Growth and germination inhibition by chloroform and methanol extracts | Damián-Badillo et al., 2008 | Mexico |
| Balantiopsaceae | *Balantiopsis cancellata* | *Cladosporium herbarum* | Growth inhibition by Phenylethyl-2-*trans*-β-methylthioacrylate (**44)** | Labbé et al., 2005 | Chile |
| Brassicaceae | *Brassica oleracea var.botrytis* | *Leptosphaeria maculans, Rhizoctonia solani, Sclerotinia sclerotirum* | Growth inhibition by caulilexins A-C (**11**-**13**) | Pedras et al., 2006 | Canada |
| | | *Alternaria alternata* | Spore germination inhibition with broccoli juice at 0.07,0.11 and 0.15µg/µL | Flores-Córdova et al., 2013 | Mexico |
| | | *Colletotrichum gloeosporiodes* | Glucoraphanin inhibited sporulation ($IC_{50}$ 0.65 µg/µL) | Lara-Viveros et al., 2014 | Mexico |

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| | *Raphanus raphanistrum L.* | *C. acutatum, F. oxysporum, B.cinerea* | Ethanolic extracts showed moderate fungistatic effect on growth and germination | Sánchez-León, et al., 2015 | Colombia |
| Boraginaceae | *Tournefortia densiflora* | *Fusarium solani, Alternaria alternata* | Sporulation and mycelial growth inhibition (MIC 11.75-16.3 mg/mL) by methanol extracts from aerial parts and roots | Lira de León et al., 2014 | Mexico |
| Cactaceae | *Opuntia ficus-indica* | *Colletotrichum gloeosporioides, Fusarium descencelulare, F. lateritium, F. moniliforme, F. oxysporum and F. solani.* | Growth inhibition by extract and lectin | Santana et al., 2009 | Brazil |
| | | *Rhizoctonia solani* | Extracts with polyphenols showed growth inhibition ($CI_{50}$ 39.4 ppm) | Castillo-Reyes et al., 2015 | Mexico |
| Caricaceae | *Carica papaya* | *Fusarium spp.* | Growth inhibition by ethanol extract at 0.625 mg/mL | Chávez-Quintal, et al., 2011 | Mexico |
| Cleomaceae | *Cleome viscosa* | *Alternaria solani* | Growth and germination inhibition by ethanol extracts at 2 mg/mL | Pupo-Blanco et al., 2011 | Cuba |
| Clusiaceae | *Garcinia mangostana* L. | *Botrytis cinerea* | Ethanol extracts from peels of fruits showed protection of cauliflower | Ángel et al., 2014 | Colombia |
| Combretaceae | *Terminalia catappa* | *Rhizoctonia solani Kühn* | Growth inhibition by aqueous extract at <0.65 mg/mL | Espejo-Quiste et al., 2008 | Cuba |
| Convolvulaceae | *Ipomoea murucoides* | *Fusarium solani, Alternaria alternata* | Sporulation inhibition (MIC 5.77-11.54 mg/mL) by ether extract from leaves | Lira de León et al., 2014 | Mexico |
| Cornaceae | *Camptotheca acuminata* | *Alternaria alternata, Epicoccum nigrum, Pestalotia guepinii, Dreschlera sp., Fusarium avenaceum* | Growth inhibition by camptothecin (**14**), trifolin (**35**) and hyperoside (**36**) at < 50µg/mL | Li et al., 2005 | USA |
| Cucurbitaceae | *Momordica charantia* | *Fusarium sp., Cladosporium sp., Curvularia sp., Alternaria sp.* | Ethanol extracts protects *Pterogyne nitens* seeds at 100, 500 and 1000 ppm | Ferreira-Medeiros, et al., 2013 | Brazil |
| Cupressaceae | *Juniperus lucayana* | *Botrytis cinerea* | Growth inhibition by widdrol (**4**) at 50 ppm | Ortiz-Nuñez et al., 2007 | Cuba |
| Euphorbiaceae | *Acalypha cuspidata* | *Fusarium solani, Alternaria alternata* | Sporulation inhibition (MIC 12.5 mg/mL) by methanol extracts from aerial parts | Lira de León et al., 2014 | Mexico |
| | *A. diversifolia* | *Fusarium solani* | Growth inhibition by dichloro-methane extract at 1 mg/mL | Niño et al., 2012 | Colombia |
| | *A. gaumeri* | *Alternaria tagetica, Colletotrichum gloeosporioides, Fusarium oxysporum, Rhizopus sp.* | Growth inhibition by ethanol extract | Gamboa-Angulo et al., 2008 | Mexico |
| | *A. subviscida* | *Alternaria alternata* | Sporulation inhibition (MIC 8.51 mg/mL) by methanol extracts from leaves | Lira de León et al., 2014 | Mexico |
| | *Croton chichinensis* | *Alternaria tagetica, Colletotrichum gloeosporioides, Fusarium oxysporum, Rhizopus sp.* | Growth inhibition by ethanol extract (Alkaloids) | Gamboa-Angulo et al., 2008 | Mexico |
| | *Euphorbia antisyphilitica* | *Colletotrichum gloeosporoides, Rhizoctonia solani, Fusarium oxyzporum, Alternaria alternata* | Growth inhibition by ellagitannin-(**34**) rich ethanolic fraction (MW 860.7 umas) | Ascacio-Valdés et al., 2013 | Mexico |
| | *Euphorbia sp* | *Fusarium solani* | Growth inhibition by dichloro-metane extract at 1 mg/mL | Niño et al., 2012 | Colombia |

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| *Fabaceae* | *Acacia penulata* | *Colletotrichum gloeosporioides* | Growth, sporulation and germination inhibition by 15,16-dihydroxypimar-8(14)-en-3-one (**5**) | Peraza-Sánchez et al., 2005 | México |
| | *Anadenanthera colubrina* | *Alternaria alternata* | Growth inhibition *in vitro* but not *in vivo* | Carvalho et al., 2011 | Brazil |
| | *Caesalpinia cacalaco* Bonpl. | *Colletotrichum lindemuthianum* | Growth and germination inhibition by phenolic compounds rich extract | Veloz-García et al., 2010 | Mexico |
| | *Calia secundiflora* | *Alternaria solani, Fusarium oxysporum, Monila fructicola,* | Growth inhibition by extracts containing quinolizidine alkaloids (cytosine, **15**) | Pérez-Laínez, et al., 2008 | Mexico |
| | *Canavalia ensiformis* | *Curvularia lunata, Penicillium herquei, Trichoderma pseudokoningii,* | Growth and germination inhibition at sub-micromolar concentration by an urease | Becker-Ritt et al., 2007 | Brazil |
| | *Crotalaria pallida* | *Fusarium oxysporum* | Growth inhibition by a 5340 Da peptide | Pelegrini et al., 2009 | Brazil |
| | *Dioclea guianensis* Benth | *Colletotrichum gloeosporioides* | Germination inhibition by a ConA-like lectin | Araujo-Filho et al., 2010 | Brazil |
| | *Geoffroea decorticans* Burkart | *Botrytis cinerea* | Germination and growth of conidia | Boiteux et al., 2015 | Argentina |
| | *Gliricidia sepium* | *Colletotrichum acutatum* | Coumarin (0.25 and 0.5%) showed fungicide activity while ortho coumaric acid at 05 % showed fungistatic effect | Urdaneta et al., 2015 | Venezuela |
| | *Glycine max* | *Curvularia lunata, Penicillium herquei, Trichoderma pseudokoningii,* | Growth and germination inhibition at sub-micromolar concentrations by an urease ($IC_{50}$ < 0.81μM) | Becker-Ritt et al., 2007 | Brazil |
| | *Luetzelburgia auriculata* | *Colletotrichum lindemuthianum, Fusarium solani, Aspergillus niger* | Growth inhibition by a 123.5 kDa-lectin | Melo et al., 2005 | Brazil |
| | *Lupinus mexicanus* | *Rhyzoctonia solani, Sclerotium solfsii, Fusarium oxysporum* | Growth inhibition by alkaloid extract (lupanine, **16**) | Zamora-Natera et al., 2008 | Mexico |
| | *Phaseolus vulgaris* L. | *C. lindemuthianum, Phaeoisariopsis griseola* | Methanol-water extracts from leaves showed growth inhibition | Noreña-Ramírez et al., 2014 | Colombia |
| | *Piscidia piscipula* | *Colletotrichum gloeosporioides* | Growth inhibition by methanol extract | Peraza-Sánchez et al., 2005 | Mexico |
| | *Pithecellobium dulce* | *Colletotrichum gloeosporioides* | Growth inhibition (by methanol extract | Peraza-Sánchez et al., 2005 | Mexico |
| | *Pongamia glabra* | *Sclerotinia sclerotiorum* | Growth inhibition by oils in combination with neem oils | Garcia et al., 2012 | Brazil |
| | *Vigna unguiculata (L.) Walp* | *C. lindemuthianum, Phaeoisariopsis griseola* | Methanol-water extracts from leaves showed growth inhibition | Noreña-Ramírez et al., 2014 | Colombia |
| | *Zuccagnia punctata* | *Phomopsis longicolla, Colletotrichum truncatum* | Growth inhibition by chloroform, and ethanol extracts (MIC 62.5-100 μg/mL) Chalcones (**39**, **40**), flavanone (**42**) and caffeoyl ester (**41**) | Svetaz et al., 2004 | Argentina |
| Juglandaceae | *Carya illinoensis* | *Phytium sp, Colletotrichum truncatun, C. coccodes, Alternaria alternata, Fusarium solani, F. vertillioides, F. sambucinum, Rhizoctonia solani* | Growth inhibition by polyphenolic extracts at 0.20 mg/L | Osorio et al., 2010 | Mexico |
| Lamiaceae | *Hedeoma multiflora* | *Aspergillus section Flavi* | Growth and germination inhibition and reduction of aflatoxins by essential oils | Bluma et al., 2008 | Argentina |
| | *Origanum vulgarae* | *Colletotrichum lindemuthianum* | Growth and germination inhibition by methanol extract | Andrade-Pinto et al., 2010 | Brazil |

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| | | *Aspergillus niger, A. flavus* | Germination and growth inhibition by essential oils in combination with those of *Rosmatinus officinalis* L. | Lima de Sousa et al., 2013 | Brazil |
| | *Ocimum gratissimum* | *Colletotrichum lindemuthianum* | Growth and germination inhibition by methanol extract | Andrade-Pinto et al., 2010 | Brazil |
| | *Rosmarinus officinalis L.* | *Alternaria spp* | Growth inhibition by acid extract at MIC 1.25µg/mL | Díaz-Dellavalle et al., 2011 | Uruguay |
| | *R. officinalis* | *Alternaria alternata* | Growth inhibition of aqueous extract in combination with *L. alba* ones. | Tagami et al., 2009 | Brazil |
| | *Salvia macrochlamys* | *Colletotrichum acutatum, C. fragariae, C. gloeosporioides,* | Growth inhibition of essential oils (Carvacrol, Thymol) | Tabanca et al., 2007 | USA |
| | *S. officinalis* | *Alternaria spp* | Growth inhibition by acid extract at MIC 1.25µg/mL | Díaz-Dellavalle et al., 2011 | Chile |
| | *S. recognita* | *Colletotrichum acutatum, C. fragariae, C. gloeosporioides,* | Growth inhibition of essential oils (Carvacrol, Thymol) | Tabanca et al., 2007 | USA |
| | *S. sclarea* | *Alternaria spp* | Growth inhibition by acid extract at MIC 1.25µg/mL and saline buffer extract at MIC 5µg/mL | Díaz-Dellavalle et al., 2011 | Chile |
| | *Satureja macrostema* | *Colletotrichum lindemuthianum, Sporothrix schenckii* | Growth and germination inhibition by chloroform and methanol extracts | Damián-Badillo et al., 2008 | Mexico |
| | *Thymus vulgaris* | *Fusarium oxysporum* | Growth inhibition by thyme essential oil | Barrera-Necha et al., 2008 | Mexico |
| | *T. vulgaris* | *Colletotrichum gloeosporoides, Rhizopus stolonifer* | Growth inhibition of essential oils *in vitro* and *in vivo* assays | Bosquez-Molina et al., 2010 | Mexico |
| | | *Colletotrichum graminicola* | Growth inhibition of aqueous extract | Tagami et al., 2009 | Brazil |
| | *Vitex gaumeri* | *Alternaria tagetica* | Growth inhibition by ethanol extract | Gamboa-Angulo et al., 2008 | Mexico |
| Lauraceae | *Cinnamomum zeylsnicum* | *Colletrichum gloeosporioides* | Growth, germination and sporulation inhibition of essential oils *in vitro* and *in vivo* assays | Landero-Valenzuela et al., 2013 | Mexico |
| | | *Fusarium oxysporum, Alternaria alternata, Geotrichum candidum, Trichoderma spp., Penicillum digitatum, Aspegillus niger* | Growth mycelial inhibition by aqueous extracts (MIC 500 ppm). Cinnamaldehyde and kaempferol were identified as Main constituent | Cáceres Rueda de León et al., 2013 | Mexico |
| | *C. verum* | *Penicillium digitatum* | Growth inhibition by 0.5 % essential oils applied into chitosan films | Ávila-Sosa et al., 2012 | Mexico |
| | *Ocotea quixos (Lam.)* | *Phytium ultimum* | Growth inhibition by essential oils (trans-cinnamaldehyde, methylcinnamate, 1,8-cineole) | Bruni et al., 2004 | Ecuador |
| Malvaceae | *Guazuma ulmifolia* | *Sclerotium cepivorum* | Hexane and dichloromethane extracts showed growth mycelial inhibition >84% at 10000 ppm | Ramírez-Aguayo, et al., 2015 | Mexico |
| | *Hibiscus cannabinus* | *Colletotrichum fragariae, C. gloeosporioides, C. accutatum* | Growth inhibition by essential oil (5-methylfurfural, benzene acetaldehyde and *n*-nonanal) | Kobaisy et al., 2001 | USA |
| | *Malva sp.* | *Gerlachia oryzae* | Growth inhibition of aqueous extract | Knaak et al., 2013 | Brazil |
| Meliaceae | *Trichila minutiflora* | *Rhizopus sp.* | Growth inhibition by ethanol extract | Gamboa-Angulo et al., 2008 | Mexico |
| Melastomataceae | *Miconia argyrophyla* | *Colletotrichum lindemuthianum* | Growth and germination inhibition by methanol extract | Andrade-Pinto et al., 2010 | Brazil |
| Musaceae | *Musa acuminata* | *Mycosphaerella fijiensis* | Growth inhibition by phenalenone compounds (**45**, **46**) | Otálvaro et al., 2007 | Colombia |
| Myrtaceae | *Corymbia citriodora* | *Pyricularia (Magnaporthe) grisea Aspergillus spp.* | Germination and sporulation total inhibition at 0.15 mg/mL of essential oil and citronellal, which | Aguiar et al., 2014 | Brazil |

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| | | *Colletotrichum musae* | is main component (61.78 %) | | |
| | *Eugenia caryophyllata* | *Fusarium oxysporum, Alternaria alternata, Geotrichum candidum, Trichoderma spp., Penicillum digitatum, Aspegillus niger* | Growth mycelial inhibition by aqueous extracts (MIC 750-800 ppm). Gallic acid and kaempferol are main constituents. | Cáceres Rueda de León et al., 2013 | Mexico |
| | *Melaleuca quinquenervia* (Cav) | *Sarocladium oryzae, Bipolaris oryzae* | Growth inhibition (100%) essential oil | Duarte et al., 2014 | Cuba |
| | *Melaleuca alternifolia* | *Macrophomina phaseolina, Sclerotinia scelrotiorum, Alternaria alternata* | Growth inhibition by essential oils at 0.2 % | Martins et al., 2010 | Brazil |
| | *Melaleuca quinquenervia* (Cav) | *Sarocladium oryzae, Bipolaris oryzae* | Growth inhibition (100%) essential oil | Duarte et al., 2014 | Cuba |
| | *Myrcia fallax* | *Colletotrichum lindemuthianum* | Growth and germination inhibition by methanol extract | Andrade-Pinto et al., 2010 | Brazil |
| | *Syzygium aromaticum* | *Fusarium oxysporum* | Growth inhibition by essential oil | Barrera-Necha et al., 2008 | |
| | | *Sclerotium cepivorum* | Growth inhibition by aqueous extract at 1% | Montes-Belmont et al., 2006 | Mexico |
| | | *Aspergillus section* Flavi | Growth and germination inhibition and reduction of aflatoxins by essential oils | Bluma et al., 2008 | Argentina |
| Piperaceae | *Piper aduncum L.* | *Sclerotinia sclerotiorum* | Growth inhibition by aqueous extract | Garcia et al., 2012 | Brazil |
| | *Piper aduncum* subsp. *ossanum* | *Curvularia lunata, Sarocladium oryzae Bipolaris oryzae* | Growth inhibition (100%) essential oil | Duarte et al., 2014 | Cuba |
| | *P. auritum* | *Curvularia lunata, Sarocladium oryzae Bipolaris oryzae* | Growth inhibition (100%) essential oil | Duarte et al., 2014 | Cuba |
| | | *Colletotrichum acutatum, C. gloeosporioides, Botrydiploida theobromae* | Growth inhibition by *n*-hexane extract and essential oil (Safrole, apiol) | Pineda et al., 2012 | Colombia |
| | *P. holtonii* | *Colletotrichum acutatum, C. gloeosporioides, Botrydiploida theobromae* | | | |
| Poaceae | *Cymbopogon nardus* | *Pyricularia (Magnaporthe) grisea Aspergillus spp. Colletotrichum musae* | Germination and sporulation inhibition at 0.15 mg/mL of essential oil and citronellal, which is main component (36.6 %) | Aguiar et al., 2014 | Brazil |
| | *Cymbopogon citratus* | *Gerlachia oryzae* | Growth inhibition by aqueous extract | Knaak et al., 2013 | Brazil |
| | | *Alternaria alternata, Bipolaris sp.* | Growth inhibition by extract ($IC_{50}$ 75.83 µg/mL) and citral ($IC_{50}$ 58.24 µg/mL) | De Lima Guimarães et al., 2011 | Brazil |
| | *C. nardus* | *Macrophomina phaseolina* | Growth inhibition by essential oils at 1.5% | Sánchez-García et al., 2008 | Cuba |
| | *Hordeum vulgare L* | *Fusarium culmorum* | *Fusarium* proteinase inhibition by proteins | Pekkarinen et al., 2003 | USA |
| | *Oryza sativa* | *Aspergillus flavus* | Growth and aflatoxins production inhibition by phenolic extracts | Dos Santos Oliveira et al., 2008 | Brazil |
| | *Triticum aestivum* | *Aspergillus flavus* | Growth and aflatoxins production inhibition by phenolic extracts | Dos Santos Oliveira et al., 2008 | Brazil |
| | *Zea mays* | *Alternaria spp* | Growth inhibition by aqueous extract at MIC 5µg/mL | Díaz-Dellavalle et al., 2011 | Chile |
| Phytolaccaceae | *Phytolacca* | *Colletotrichum* | Conidial production and growth | Hernández et | Argentin |

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| | *tetramera* | *gloeosporioides* | inhibition by ethanol and aqueous extracts | al., 2013 | a |
| | *Petiveria alliaceae* | *Gerlachia oryzae* | Growth inhibition by aqueous extract | Knaak et al., 2013 | Brazil |
| Primulaceae | *Jacquinia macrocarpa* | *Fusarium verticillioides* | A fraction from a butanol partition showed growth inhibition (100%) | Valenzuela-Cota et al., 2014 | Mexico |
| Rubiaceae | *Galium mexicanum* | *Fusarium solani, Alternaria alternata* | Sporulation inhibition (MIC 15 mg/mL) by methanol extracts from aerial parts | Lira de León et al., 2014 | Mexico |
| Rutaceae | *Amyris texana* | *Botrytis cinerea* | Growth inhibition by a chromene amide (**10**) | Meepagala et al., 2010 | USA |
| | *Citrus aurantifolia* | *Colletotrichum gloeosporioides, Rhizopus stolonifer* | Growth inhibition of essential oils *in vitro* and *in vivo* assays | Bosquez-Molina et al., 2010 | Mexico |
| | | *Aspergillus nidulans, Colletotrichum acutatum* | Conidia survival reduction by coumarins (22, 23, 26, 27) and furocoumarins (24, 25, 28, 29) under photo treatment | De Menezes et al., 2014 | Brazil |
| | *C. sinensis* | *Bipolaris oryzae* | Growth inhibition (100%) essential oil | Duarte et al., 2014 | Cuba |
| | *Ruta graveolens L.* | *Colletotrichum acutatum, Botrytis cinerea* | Growth inhibition by furanocumarins and alkaloids (**19**, **20**, **21**) | Oliva et al., 2003 | USA |
| | *Zanthoxylum fagara* | *Colletotrichum acutatum, Fusarium oxysporum,* | Growth inhibition by essential oils (germacrene, elemol amd α-cadinol) | Prieto et al., 2011 | Colombia |
| | *Z. rhoifolium* | *Fusarium oxysporum, Colletotrichum acutatum* | Growth inhibition by essential oils (β-myrcene, β-phellandrene and germacrane D) | Prieto et al., 2011 | Colombia |
| | *Z. monophyllum* | *Fusarium oxysporum Sitophilus oryzae, Colletotrichum acutatum* | Growth inhibition by essential oils (sabinene, 1.8-cineole and α-cadinol) | Prieto et al., 2011 | Colombia |
| Sapindaceae | *Matayba elaeagnoides* | *Colletotrichum lindemuthianum* | Growth and germination inhibition by methanol extract | Andrade-Pinto et al., 2010 | Brazil |
| Siparunaceae | *Siparuna arianeae* | *Colletotrichum lindemuthianum* | Growth and germination inhibition by methanol extract | Andrade-Pinto et al., 2010 | Brazil |
| Solanaceae | *Capsicum annum var. glabriusculum* | *Alternaria alternate, Fusarium oxysporum* | Conidial germination inhibition (85.3-96%) of phenolic and carotene extracts from fruits | Rodriguez-Maturino et al., 2015 | Mexico |
| | *Solanum lycopersicum* | *Moniliophthora perniciosa* | Growth inhibited by alfa-tomatine isolated from leaves | Gomes et al., 2014 | Brazil |
| | *Solanum tuberosum L-* | *Aspergillus flavus* | Mycelial growth and aflatoxins production inhibition by phenolic compounds | Dos Santos Oliveira et al., 2008 | Brazil |
| Styracaceae | *Styrax pohlii* | *Colletotrichum lindemuthianum* | Growth and germination inhibition by methanol extract | Andrade-Pinto et al., 2010 | Brazil |
| Verbenaceae | *Lantana achyranthifolia* | *Fusarium monoliforme* | Growth inhibition by essential oils (carvacrol, isocaryophyllene) at $IC_{50}$ 100-180μg/mL | Hernández et al., 2008 | Mexico |
| | | *F. solani, Alternaria alternata* | Sporulation inhibition (MIC 6.25-12.5 mg/mL) by methanol extract from leaves | Lira de León et al., 2014 | Mexico |
| | *L. camara* | *Alternaria solani* | Growth and germination inhibition of ethanol extracts | Pupo-Blanco et al., 2011 | Cuba |
| | | *Bipolaris oryzae* | Growth inhibition by aqueous extract | Knaak et al., 2013 | Brazil |
| | *Lippia alba* | *Alternaria spp* | Growth inhibition by acid and saline extract at MIC 25 μg/mL | Díaz-Dellavalle et al., 2011 | Chile |
| | *L. dulcis* | *Alternaria solani* | Growth and germination inhibition of ethanol extracts | Pupo-Blanco et al., 2011 | Cuba |
| | *L. graveolens* | *Aspergillus niger, Trichophyton* | Growth inhibition by essential oils (carvacrol, α-terpinyl acetate, *m*- | Hernández et al., 2008 | Mexico |

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|---|---|---|---|---|---|
| | | *mentagrophytes, Rhyzoctonia solani, Fusarium sporotrichum, F. monoliforme, Aspergillus niger* | cymene) at $IC_{50}$ 10-90µg/mL | | |
| | | *Rhizopus stolonifer, Colletotrichum gloeosporioides, Penicillium digitatum* | Growth and sporulation inhibition of ethanol extract at 500-3000µl/L | Jasso de Rodríguez et a., 2011 | Mexico |
| | *L. berlandieri Schauer* | *Aspergillus niger* | Growth inhibition by 0.5 % essential oils applied into chitosan films | Ávila-Sosa et al., 2012 | Mexico |
| | *L. berlandieri* | *Fusarium oxysporum, Alternaria alternata, Geotrichum candidum, Trichoderma spp., Penicillum digitatum, Aspegillus niger* | Growth mycelial inhibition by aqueous extracts (MIC 200-250 ppm). Gallic acid, carvacrol, thymol and caryophyllene were identified as main constituents | Cáceres Rueda de León et al., 2013 | Mexico |
| | *L. turbinata var Integrifolia* | *Aspergillus section Flavi* | Growth and germination inhibition and reduction of aflatoxins by essential oils | Bluma et al., 2008 | Argentina |
| Winteraceae | *Drimys winteri* J.R. Forst. & G. Forst. | *Gaeumannomyces graminis* | Growth inhibition by essential oil (α-pinene,β-pinene, limonene, β-myrcene) and *n*-hexane extract containing polygodial (**6**), drimenol (**7**), drimenin (**8**), isodrimenol (**9**) | Monsálvez et al., 2010 | Chile |
| Xanthorrhoeaceae | *Aloe vera* | *Alternaria spp.* | Growth inhibition by acid extract at MIC 25 µg/mL | Díaz-Dellavalle et al., 2011 | Chile |
| Zingiberaceae | *Zingiber officinale* | *Bipolaris oryzae, Gerlachia oryzae* | Growth inhibition of aqueous extract and essential oil | Knaak et al., 2013 | Brazil |
| Zygophyllaceae | *Larrea cuneifolia* | *Fusarium oxysporum, Penicillium notatum, Aspergillus niger* | Growth inhibition by ethanol extract | Quiroga et al., 2001 | Argentina |
| | *Larrea divaricata* | *Fusarium graminearum. F. solani, F. verticillioides, Macrophomina phaseolina* | Growth inhibition by chloroform extract and phenolic compounds (**38**) MIC 12.5-250 µg/mL | Vogt et al., 2013 | Mexico |
| | | *Penicillium notatum, Aspergillus niger, Fusarium oxysporum* | Growth inhibition by ethanol extract | Quiroga et al., 2001 | Argentina |
| | *L. tridentata* | *Phytium sp, Colletotrichum truncatun, C. coccodes, Alternaria alternata, Fusarium solani, F. vertillioides, F. sambucinum, Rhizoctonia solani* | Growth inhibition by mono and polyphenolics rich extracts at 0.20 mg/L | Osorio et al., 2010 | Mexico |
| | | *R. solani* | Extracts with polyphenols showed growth inhibition ($CI_{50}$ 58.4 ppm) | Castillo-Reyes et al., 2015 | Mexico |
| | | *R. solani* | Lanolin extract produces growth inhibition ($CI_{50}$ 185 ppm ) | Castillo et al., 2010 | Mexico |

(8, 9) were toxic to *Monilia, Alternaria, Fusarium* and *Rhizoctonia* species (Pérez-Laínez et al., 2008; Zamora-Natera et al., 2008). Coumarins as 4-hydroxycoumarin, 7-hydroxycoumarin, 7-methoxycoumarin (14), 8-methoxypsolaren, citropten (15), 5-methoxypsolaren (16), and isopimpinellin (Figure 1) were described with antifungal activity against *Colletotrichum* and *Aspergillus* (De Menezes et al., 2014), and the closely related multisicoumaranones A (17), B, C and D, resulted toxic to *Cladosporium* species (Viturro et al., 2004). Phenolic and polyphenolic compounds (Figure 1) of twelve vegetable species have shown broad-spectrum fungicide activity against eleven fungus genera, the active compounds isolated are ellagitannin (18), trifolin (19), hyperoside (20), lignans (21, 22), chalcones (23, 24), a caffeic acid derivative (25) and flavanone (26). About antifungal mechanisms, it was reported that the compound 22 is a fungal endo-β-(1,3)-glucanase inhibitor (Vargas-Arispuru et al., 2009). Others active compounds (Figure 1) are acetylenic lactone (27) (Queiroz et al., 2012), 2-phenylethanol ester (28) (Labbé et

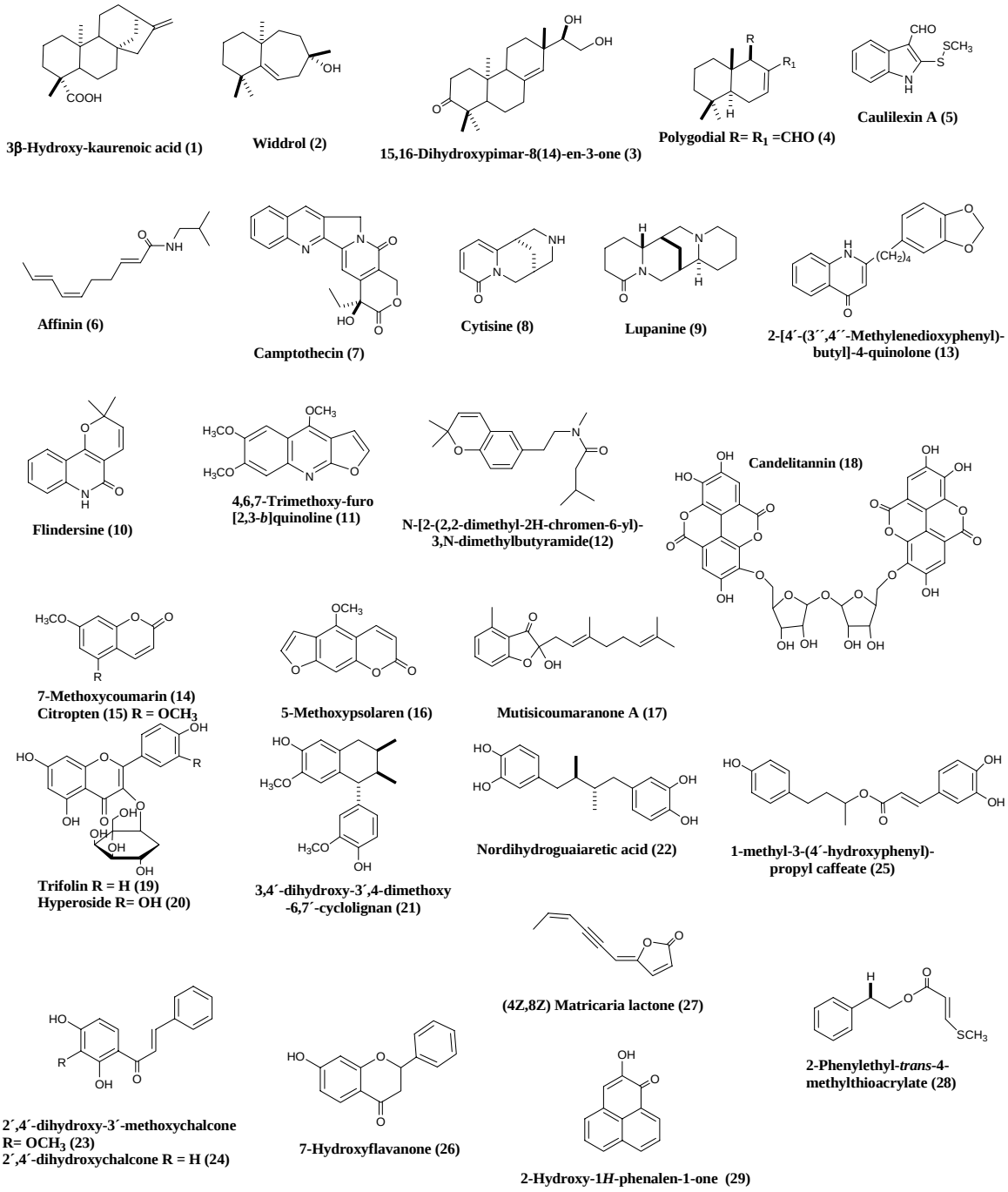


**Figure 1. Structures of compounds of vegetable origin with fungicide activity identified in the American continent**

al., 2005), and the unusual 2-hydroxy-1-*H*-phenalen-one (**29**) and 2-methoxy-1-*H*-phenalen-one, which are fungicides against *Colletotrichum*, *Cladosporium*, and *Mycosphaerella*, respectively (Otálvaro et al., 2007). Other compound also toxic to *Colletotrichum* was the known glucosinolate glucoraphanin, isolated from *Brassica oleracea* (Lara-Viveros et al., 2014)

Plants are able to produce proteinaceous compounds, between those described with fungicide activity are lectins (glycoproteins that agglutinate and immobilize micro-organisms) and microbial proteinase inhibitors (inhibit enzymes that degrade plant cell walls). Examples of lectins and fungal proteinase inhibitors with toxic activity on phytopathogen fungus are those isolated from *Dioclea guianensis* (Araújo-Filho et al., 2010), *Luetzelburgia auriculata* (Melo et al., 2005), *Calotropis procera* (De Freitas et al., 2011) and *Hordeum vulgare* (Pekkarinen and Jones, 2003) (Table 3). In addition, the binding of ConA-like lectin with ungerminated conidia of C*olletotrichum gloeosporioides* inhibit the germination (Araújo-Filho et al., 2010). But when the lectin interact with outer portion of cell wall and inner surface, the synthesis of fungal cell or cell

wall structure and function are disrupted. Such is the case of growth inhibition by agglutinin (LAA) isolated from *Lutzelburgia auriculata*, which inhibited the fungal growth and provoked interference on the transport of intracellular protons to the external medium (Melo et al., 2005). Other proteinaceus compounds are ureases; nickel-dependent metalloenzymes that catalyze the hydrolysis of urea to ammonia and carbon dioxide, as those described from *Glycine max*, which produced plasmolysis and cell wall injuries during the growth of *Curvularia lunata, Penicillium herquei* or *Trichoderma pseudokoningii* (Becker-Ritt et al., 2007).

## CONCLUSIONS

The development of organic agriculture as projected by FAO (2009) may increase the use of biofungicides where few alternative pesticides are accessible. Even though that the eco-friendly fungicides are more pertinent for use in industrialized countries for the organic food production, they can play a much important role in the protection of food products in developing countries. Nowadays, there are more than 100 kinds of biopesticides in the world (Xu, 2008). The countries that use more biopesticides in the world are Mexico, Canada and the United States (44% global production), while Latin America and the Caribbean accounts for 9% (Qin and Kong, 2006). The developing countries are the source of endemic plants and this may have a great impact in improving food safety, through the production of biopesticides to promote food security. The majority of the evidences of fungitoxicity of plant extracts presented in this review were supported from *in vitro* evaluations, it is imperative to test the bioactive extracts on farm investigations under natural infections against a wide range of pathogens. The challenges to commercial application of plant extracts as biofungicides include the availability of plant material, efficacy at least equivalent to the current pesticide used, not toxicity against crop plants and that no compromise the quality of the crops. Moreover, as the phytochemicals profile of plant species can vary depending on climatic, geographic or genetic factor, among others, biofungicides manufacturers must to ensure that their products have a consistent and standardized composition. As the secondary metabolites occur in mixtures in the crude extracts, a good option is the guide-isolation and purification of the bioactive fungicide compounds, in order to elucidate their mechanisms of action, improve their effectiveness and enhance their production in the plant.

In summary, sustainable food security cannot rely on the use of synthetic pesticides, endemic resources of biopesticides must be utilized in the production and post harvest protection of food products in developing countries, in order to ensure that the populations will have access to sufficient and healthy food.

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